

A Different Approach to Galaxy Evolution

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ABSTRACT

The consequences are explored of an observationally established relation of the star formation rate (SFR) of star-forming galaxies with their stellar mass (M) and cosmic time (t), such that $\text{SFR} \propto M t^{-2.5}$. It is shown, that small systematic differences in SFR dramatically amplify in the course of time: galaxies with above average SFR run into quasi-exponential mass and SFR growth, while galaxies with below average SFR avoid such exponential growth and evolve with moderate mass increase. It is argued that galaxies following the first path would enormously overgrow if keeping to form stars all the way to the present, hence should quench star formation and turn passive. By the same token, those instead avoiding the quasi-exponential growth may keep to form stars up to the present. Thus, it is conjectured that this divergent behaviour can help understanding the origin of the dichotomy between passive, spheroidal galaxies, and star-forming, disk galaxies.

Key words: galaxies: evolution – galaxies: high redshift – galaxies: formation

1 INTRODUCTION

In this paper I propose a different approach towards understanding galaxy evolution. Instead of starting from first physical principles and proceed deductively, as in the widely explored Λ CDM approach, I will attempt a fully *inductive*, bottom-up approach based exclusively on few established empirical evidences.

Indeed, in recent years a formidable body of multiwavelength data have been accumulated on galaxies at all redshifts up to ~ 6 . Such data are especially extended for $z \lesssim 3$, hence encompassing the major epoch of galaxy growth peaking at $z \sim 2$, when the morphological differentiation into (spiral) disks and (elliptical) spheroids is well under way. Various multiwavelength photometric and spectroscopic databases have allowed several groups to derive major galaxy quantities such as redshifts, star formation rates (SFR), stellar masses (M), etc.

One important result of these observational studies, based on the GOODS database (Giavalisco et al. 2004; Vanzella et al. 2008, and references therein) was the recognition that at $1.4 \lesssim z \lesssim 2.5$ the SFR of star-forming (SF) galaxies tightly correlates with the stellar mass, with $\text{SFR} \propto M$, while some galaxies have already ceased to form stars and evolve passively (Daddi et al. 2007). As illustrated in Figure 1, at these redshifts galaxies are either actively star forming, or already passive, with very few galaxies lying out of these two main branches, i.e., the active branch with $\text{SFR} \propto M$, and the passive one with $\text{SFR} \sim 0$. These evidences lead to recognize that the vast majority of the SF galaxies are not in a starburst phase, even if their SFRs are hundreds of $M_\odot \text{yr}^{-1}$. Instead, they are steadily forming stars at high rates over a major fraction of the ~ 2 Gyr of cosmic time from $z \sim 3$ to $z \sim 1.4$.

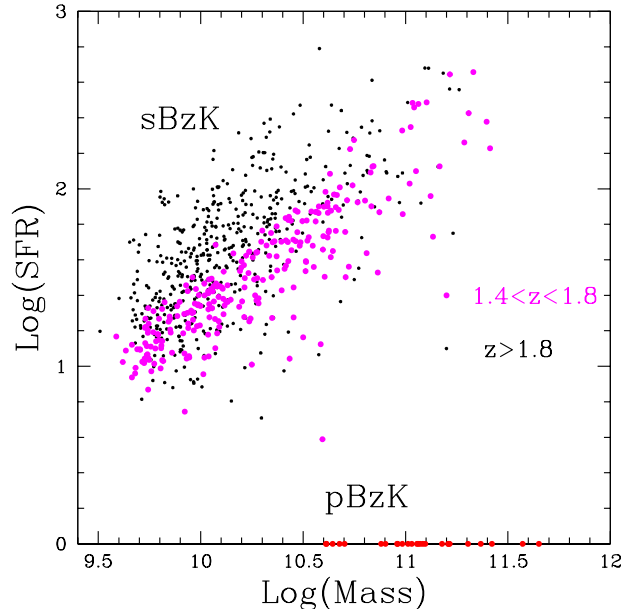


Figure 1. The star formation rate vs. stellar mass (respectively in $M_\odot \text{yr}^{-1}$ and M_\odot) for BzK -selected galaxies at $1.4 < z < 2.5$ in the GOODS-South field (from Daddi et al. 2007). The SFR was derived from the UV flux plus extinction correction. Galaxies cluster either on the star-forming branch (sBzK) or on the passive branch (pBzK) with star formation rate $\text{SFR} \approx 0$, displayed here at $\text{Log}(\text{SFR})=0$. Notice that very few galaxies lie in between the two main branches, indicative of SF quenching being a fast process.

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The same pattern, with galaxies lying either on a tight SF branch with $\text{SFR} \propto M$ or being already passive, has then been recognized also at lower redshifts, from $z \sim 1$ (Elbaz et al. 2007), all the way to $z \sim 0$, hence revealing a steady decrease of the SFR of galaxies in the SF branch, which at fixed mass is by a factor ~ 30 between $z \sim 2$ and $z \sim 0$ (Daddi et al. 2007, see their Fig. 17). Due to its tightness, the SF branch has been dubbed the *main sequence* of SF galaxies (Noeske et al. 2007).

In Daddi et al. (2007) the SFRs of $1.4 \lesssim z \lesssim 2.5$ galaxies have been derived with the traditional method based on the rest-frame UV flux, plus extinction correction from the slope of the UV continuum. SFRs in full agreement with these UV-derived ones have been recently obtained from stacking the 1.4 GHz fluxes of $\sim 12,000$ SF galaxies in the COSMOS field (Pannella et al. 2009), hence confirming the reliability of the classical procedure for the extinction correction. In particular, an almost perfect linear relation of the SFR with M is recovered, hence implying a specific SFR (SSFR = SFR/M) independent of mass. As in Daddi et al. (2007), $1.4 \lesssim z \lesssim 2.5$ galaxies were selected using the *BzK* criterion introduced by Daddi et al. (2004), and applying it to the deep *K*-band selected catalog of galaxies in the COSMOS field (McCracken et al. 2009).

Combining their own data for galaxies at $1.4 \lesssim z \lesssim 3$ with those at $z \sim 1$ (Elbaz et al. 2007), $z \sim 0.7$ (Noeske et al. 2007) and $z \sim 0$ (Brinkmann et al. 2004), Pannella et al. (2009) have then obtained the following best-fit relation for galaxies on the SF branch:

$$\langle \text{SFR} \rangle \simeq 270 \times \eta M_{11} (t/3.4 \times 10^9)^{-2.5} \quad (M_{\odot} \text{yr}^{-1}), \quad (1)$$

where M_{11} is the stellar mass in units of $10^{11} M_{\odot}$, and t is the cosmic time in years. The factor $\eta = \text{SFR}(t = 3.4 \times 10^9)/270$ has been introduced here, with $\eta \equiv 1$ for the best fit relation presented by Pannella et al. (2009), but the effects of assuming other values will be also investigated. Note that a quite similar relation, consistent with Eq. (1), can be derived from Fig. 17 in Daddi et al. (2007).

SFRs and stellar masses used in establishing Eq. (1) were obtained assuming a Salpeter (1955) initial mass function (IMF). Adopting other IMFs such as those of Kroupa (2001) or Chabrier (2003) would affect SFRs and masses by the same factor, thus leaving SSFRs unchanged. Therefore, none of the results presented in this paper depends on the adopted IMF, provided it does not vary from one galaxy to another (e.g., as a function of mass), or from one cosmic time to another. If this were the case, the net effect would be to change the exponents of M and/or t in Eq. (1), a possibility that is not further explored in this paper given the unconstrained nature that such an exercise would have.

I now explore the consequences of assuming that Eq. (1) adequately describes the evolution of the SFR for galaxies in the SF branch from $z \sim 3$ ($t \sim 2$ Gyr) all the way to $z \sim 0$ ($t \sim 13.7$ Gyr).

Before exploiting this relation, it is worth mentioning that other studies find SSFRs markedly declining with mass (e.g., Erb et al. 2006; Cowie & Barger 2008). Dunne et al. (2008) have discussed this kind of discrepancies and their possible origin, and confirm a SSFR nearly independent of mass at $z \sim 2$, as most recently found by Santini et al. (2009) for galaxies in the GOODS-South field. Notice also that Noeske et al. (2007) find $\text{SFR} \propto M^{2/3}$ for $z \lesssim 1$ galaxies on the SF branch. Hence the exponent of M_{11} in Eq. (1) may not be strictly 1, and it may slightly evolve with redshift (cf. Dunne et al. 2008). Still, for the present exercise I explore the implications of Eq. (1) taking it at face value in the redshift interval $0 < z < 3$.

2 THE GROWTH OF GALAXIES

Eq. (1) also describes as the stellar mass of individual galaxies grows as a result of their star formation, and does so as a function of stellar mass and time. Hence, one can integrate the equation $dM/dt = \text{SFR}$, with SFR given by the right hand side of Eq. (1). This leads to a galaxy growth with time described by the equation:

$$\frac{M(t)}{M(2 \text{ Gyr})} \simeq \exp(13.53 \eta) \exp(-38.26 \eta t^{-1.5}), \quad (2)$$

which represents the growth factor of galaxy mass as a function of cosmic time. Notice that it is not attempted here to explore galaxy evolution beyond $z = 3$ ($t \lesssim 2$ Gyr), as Eq. (1) is observationally established only for $z \lesssim 3$, but just to follow the mass growth from $t \sim 2$ Gyr onwards. Combining Eq. (1) and (2) one then derives the corresponding evolution with time of the SFR of individual galaxies:

$$\frac{\text{SFR}(t)}{\text{SFR}(2 \text{ Gyr})} = 5.66 \times \frac{M(t)}{M(2 \text{ Gyr})} \times t^{-2.5}. \quad (3)$$

One intriguing aspect of the SFR as given by Eq. (1) is that its normalization η appears at the exponential in Eq. (2) and (3). Hence, the effects of relatively small differences in η dramatically amplify as time goes by. This is illustrated in Fig. 2 where the cases with $\eta = 1, 1/2$ and $1/4$ are shown. Let us first focus on the $\eta = 1$ case. Notice the extremely rapid growth of the stellar mass, amounting to more than a factor $\sim 10^5$, if Eq. (1) were to hold true from $t = 2$ Gyr to the present (from $z \sim 3$ to $z = 0$). Clearly, observations do not support such a dramatic overgrowth. However, with $\eta = 1/4$, i.e., just a factor of 4 lower SFR for given mass and time, the corresponding growth is much smaller, i.e., just a factor ~ 30 .

The parameter η is meant to describe two independent aspects of Eq. (1): (i) exploring the effects of a possible systematic offset of the derived SFRs, which certainly cannot be currently excluded, and (ii) explore the effect of departures of the SFRs of individual galaxies from the average, i.e., for being systematically higher/lower than the average by a factor η . For the first aspect, Fig. 2 shows that the true value of the SSFR at given time critically determines the subsequent grow rate of the stellar mass of galaxies: a factor of just a few difference making enormous differences in the subsequent evolution. This means that the average SSFR would need to be measured with extreme accuracy in order to accurately predict such a subsequent evolution. Current systematic SFR uncertainties are indeed by a factor of ~ 2 or 3, hence η in Eq. (1) will have to be used as an adjustable parameters within these observational uncertainties.

The second aspect is perhaps more attractive. It implies that at given mass and cosmic time galaxies whose SSFR differ by a relatively small factor experience radically different mass evolutions: some enjoy a rather modest mass growth, with secularly declining SFRs, while others suffer a runaway, quasi-exponential mass growth, which certainly cannot be sustained for more than ~ 1 Gyr. Eq. (1) refers to the *average* SFR, hence quite naturally one expects some galaxies to have SFRs systematically lower than the average, and others to have it higher than the average. However small this dispersion can be, it naturally tends to dramatically amplify in the course of time, as demanded by Eqs (2) and (3) and illustrated in Fig. 2 and Fig. 3.

The likely origin of such a dispersion is environment. As mentioned above, the tight SF branch of galaxies indicates that they experience (quasi-)steady SF. This picture is in agreement with recent hydrodynamical simulations in which SF in galaxies is continuously fed by *cold stream* gas accretion from the environment

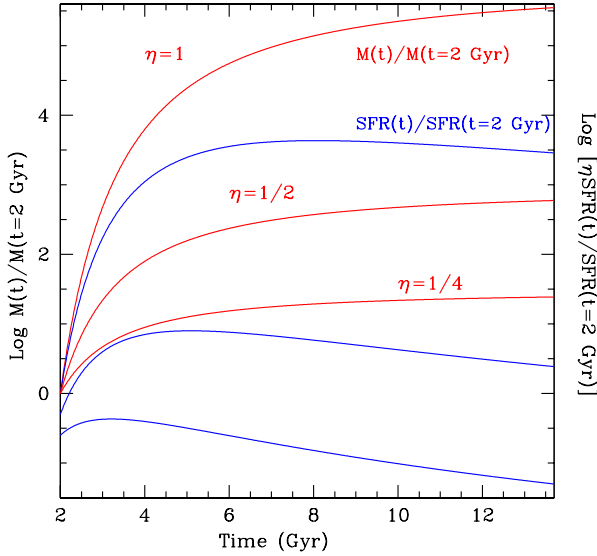


Figure 2. The growth with cosmic time of the stellar mass normalised at its initial value at $t = 2$ Gyr ($z \sim 3$), following Eq. (1) and (2), and for three values of η as indicated. Also shown is the corresponding evolution with time of the SFR, following Eq. (3), for the same values of η . The three curves are initially offset by a factor η to show the initial difference in their SFRs (i.e., at $t = 2$ Gyr). One can appreciate that SFRs for given mass and time that differ by only a factor of a few lead to vastly different evolutionary paths.

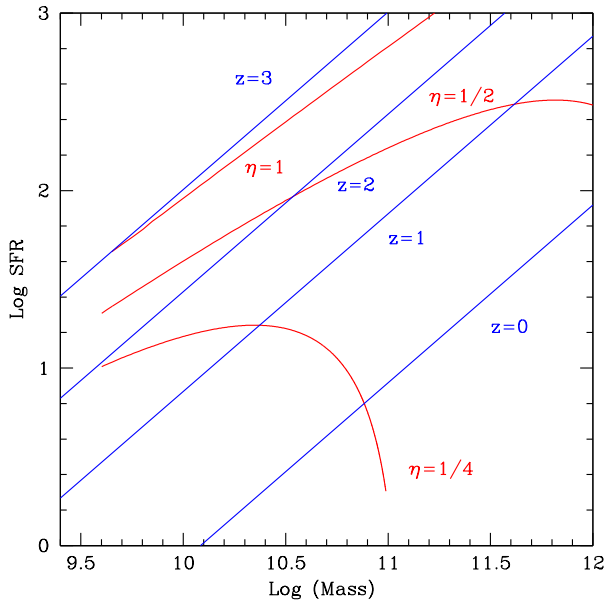


Figure 3. The evolution of stellar mass and SFR for galaxies which at $t = 2$ Gyr start with $M = 4 \times 10^{10} M_{\odot}$, for the three different values of η also used for Fig. (1). The straight lines show the SFR-mass relation from Eq. (1) at four different redshifts and with $\eta = 1$.

(Dekel et al. 2009). Therefore, galaxies in different environments are likely to experience different rates of gas accretion, hence different SSFRs. Actually, Eq. (1), in spite of its simplicity, may capture both *nature* and *nurture* aspects of galaxy evolution, which to some extent undoubtedly must co-exist. Indeed, the stellar mass, certainly a main driver in galaxy evolution, clearly stands for *nature*, and a dispersion of η results from a dispersion in the physical properties of the local environment of individual galaxies (*nurture*). Moreover, the $t^{-2.5}$ factor in Eq. (1) describes the global, cosmological evolution of the environment, a combination of cosmic expansion and the progressive consumption of the cold-gas reservoir, as more baryons are shock heated to virial temperatures, or even above it by feedback effects (galactic winds).

Notice that in galaxies undergoing rapid mass accretion ($\eta \gtrsim 1$) the SFR increases quasi-exponentially with time, i.e., just the opposite of what assumed in the so-called τ -models in which SFR decreases exponentially with time. The unfitness of such models to describe some major aspects galaxy evolution was pointed out in Cimatti et al. (2008) and is further explored in Maraston et al. (2009, in preparation).

3 A CONJECTURE ON THE ORIGIN OF MORPHOLOGICAL DIFFERENTIATION

The origin of the sharp separation into the early-type (spheroid) and late-type (disk) families of galaxies remains a central question in galaxy evolution studies. Based on the above arguments, I would like to propose here a conjecture that may help understanding the origin of this dichotomy. I assume that Eq. (1) for the average SFR holds true for SF galaxies with $\eta = 1$ (but a slightly lower value of η may work even better, see below). Then individual galaxies evolve according to Eq.s (2) and (3), each with its specific value of η , with a dispersion of η values similar to the empirical dispersion of the SFRs shown in Fig. 1. In practice, a range of η within a factor 3 – 4 about its mean value should encompass the vast majority of galaxies in the SF branch.

As shown in Fig. 2, galaxies with $\eta \gtrsim 1$ undergo extremely fast mass growth that cannot be sustained indefinitely. At some point in time a SFR as given by the r.h.s. of Eq. (1) cannot apply any longer, which is to say galaxies must leave the SF branch described by Eq. (1). As suggested by Pannella et al. (2009), the only way this can happen is by quenching completely SF, thereby galaxies join the passive branch (indeed, they have no other place to go in Fig. 1). This SF quenching can happen in a variety of ways. Just to mention one, extremely high gas accretion by, and SF rates in, massive disks at $z \sim 2$ likely results in disk instabilities, with massive clumps coalescing at the center to form a bulge, feeding an AGN and its ensuing feedback (Immeli et al. 2004; Elmegreen & Elmegreen 2006; Genzel et al. 2008).

Galaxies with sub-average gas accretion and SFR ($\eta \lesssim 1$), on the contrary, avoid the quasi-exponential mass and SFR growth; their mass increases moderately and they exhibit a slowly decreasing SFR over most of the cosmic time (Fig. 2 and Fig. 3). Disk galaxies with sub-average SFRs are therefore likely to avoid global disk instabilities, hence retaining their disk structure all the way to the present.

Notice also that those galaxies that experience a quasi-exponential growth naturally develop an α -element enhancement, that is typical of ellipticals and bulges (e.g., Thomas et al. 2005; Zoccali et al. 2006). Instead, those galaxies that avoid a quasi-exponential growth experience a chemical enrichment to which

both supernova types contribute substantially, hence resulting in near-solar abundance ratios.

In summary, the tenet of the conjecture is that the morphological differentiation of galaxies is the result of a SSFR (almost) independent of mass working as a very efficient amplifier of galaxy to galaxy differences of SSFR. Galaxies with above-average SFRs experience a runaway mass accretion resulting in global instabilities and spheroid formation. Instead, those with sub-average SFRs experience only a modest mass growth, avoid instabilities, and survive as disks. Differences in SSFR likely arise from differences in cold gas accretion from the environment, which can also help understanding the origin of the morphology-density relation.

4 CAVEATS

This scenario completely neglects mergers, and assumes *in situ* SF as the only process leading to the growth of galaxy mass. In recent years there has been a marked shift of emphasis from (major) mergers to cold stream accretion as the main driver of galaxy evolution (Genzel et al. 2008; Dekel et al. 2009, and references therein). Even so, mergers must occur and play a role that may indeed be dominant at very high redshifts (say, $z \gtrsim 3$), but then steadily decline (e.g., Masjedi, Hogg & Blanton 2008; Conselice, Yang & Bluck 2009) and is superseded by cold stream accretion (Dekel et al. 2009). In any event, a full description of galaxy evolution must also include merging processes. Like done here for star formation alone, one could include this effect using empirical merger rates once they are firmly established.

In the simplified approach presented here, it is assumed that SF galaxies evolve following Eq.s (2) and (3), each with a fixed value of η . Actually, gas accretion and ensuing SFR must fluctuate up and down as a function of time, an aspect that indeed may be regarded as a series of *minor merger* events (Dekel et al. 2009). So, the evolution of individual galaxies cannot be so smooth as implied by Eq.s (2) and (3) and shown in Fig. 2. Yet, apart from short timescale fluctuation, one should expect that different galaxies (in different environments) experience systematically higher/lower than average gas accretion and SF rates, once averaged over sufficiently long timescales. It is indeed this kind of *noise suppressed* evolution that is described by Eq.s (2) and (3).

On the other hand, as clear from Fig. 2, what matters most is the value of η during the relatively short interval of cosmic time ($2 \lesssim t \lesssim 4$ Gyr) when the quasi-exponential growth may or may not take place. Later, the SFR tends to decrease (and the mass growth to slow down) no matter what the value of η is, as the factor $t^{-2.5}$ begins to dominate. Actually, it is unlikely that environmental effects on SFRs maintain the same direction at all redshifts. For example, overdensity may promote higher SFRs at high z when cold gas is more abundant, but at low z overdense regions such as clusters may become detrimental to SF, as most gas has been shock-heated to high temperatures within the cluster potential well. Thus, typical values of η are likely to depend on a non separable combination of overdensity and cosmic epoch.

5 PERSPECTIVES

As the mapping of the galaxy populations at high redshifts progress, along with that of their large scale structure distribution, it becomes increasingly urgent to our curiosity trying to understand

what galaxies at some high redshift become at another, lower redshift. For example, whether some SF disks in a certain environment are more likely to remain SF disks, or will suffer a major, catastrophic event turning them into passive spheroids. The conjecture presented here may help identifying one of the major mechanisms driving galaxy evolution, including its bifurcation into SF disks and passive spheroids. Yet, certainly many critical issues remain open.

First, nothing is said here on the evolution prior to $t = 2$ Gyr, i.e. on how galaxy form and grow during the first 2 billion years of cosmic evolution. Available data at $z > 3$ are presently insufficient to attempt an empirical approach similar to that followed here at lower redshifts.

Assuming an empirically motivated stellar mass function for galaxies at $z = 3$, Eq. s (1), (2) and (3) can in principle be used to evolve such mass function to lower redshifts. Such an evolution would be critically dependent on several assumptions, worth mentioning and discussing them here:

1) The average value of η , i.e., the absolute normalization of the SSFR in Eq. (1). All estimates, including those of Daddi et al. (2007) or Pannella et al. (2009) adopted here, are certainly affected by a systematic error, hard to pinpoint from observations. As alluded above, one can suspect that an average η somewhat less than 1 (e.g., $\eta \sim 1/2$) may give a more realistic share between galaxies running into catastrophic growth and those evolving more peacefully. Critical to emphasize here is the important role played by such a normalization.

2) The dispersion of η values, which along with the average η concur in determining the evolution of the mass function.

3) The SF quenching mechanism, and its dependence on galaxy mass, environment, and cosmic epoch. We empirically know, from evidences at low (Thomas et al. 2005) as well as high redshifts (e.g., Cimatti, Daddi & Renzini 2006; Renzini 2006; Bundy et al. 2006; Cimatti et al. 2008), that massive galaxies are the first to turn passive, around $z \sim 2$. Then, as time goes by, a fraction of galaxies of lower and lower masses cease to form stars, while others maintain such activity all the way to the present. This mass phasing of the SF quenching process is not a natural consequence of the conjecture presented in Section 3, and requires additional physics besides the mass-dependent SFR given by Eq. (1). Indeed, a SSFR for actively SF galaxies that is independent of mass inherently does not include a *downsizing* effect, as all masses grow at the same relative rate (see Pannella et al. 2009). Hence, downsizing in SF quenching must involve physical phenomena that are not described by a SSFR(M, t) relation for SF galaxies.

4) Assuming that minor, gas-rich mergers are automatically included in Eq. (1), the effects of major mergers are left out by such an approach, a limitations that could again be alleviated with either empirically or theoretically motivated mergers rates.

In conclusion, playing with these assumptions and exploring the parameter space may in the future help our understanding of galaxy evolution. For the time being, I just wish to emphasize that an empirical relation between SFR, stellar mass, and cosmic time naturally predicts an extreme amplification of small differences in SFR during their major epoch of SF at $z \sim 2$.

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REFERENCES

- Brinchmann, J., Charlot, S., White, S. D. M., Tremonti, C., Kauffmann, G., Heckman, T., Brinkmann, J., 2004, MNRAS, 351, 1151
- Bundy, K., Ellis, R.S., Conselice, C.J. et al., 2006, ApJ, 651, 120
- Chabrier, G. 2003, PASP, 115, 763
- Cimatti, A., Daddi, E., Renzini, A., 2006, A&A, 453, L29
- Cimatti, A., Cassata, P., Pozzetti, L., et al., 2008, A&A, 482, 21
- Conselice, C.J., Yang, C., Bluck, A.F.L. 2009, MNRAS, 394, 1956
- Cowie, L.L., Barger, A.J., 2008, ApJ, 686, 72
- Daddi, E., Cimatti, A., Renzini, A., Fontana, A., Mignoli, M., Pozzetti, L., Tozzi, P., Zamorani, G., 2004, ApJ, 617, 747
- Daddi E., Dickinson, M., Morrison, G., et al., 2007, ApJ, 670, 156
- Dekel, A., Birnboim, Y., Engel, G., et al., 2009, Nature, 457, 451
- Dunne, L., Ivison, R. J., Maddox, S., et al., 2009, MNRAS, 394, 3
- Elbaz D., Daddi, E., Le Borgne, D., et al., 2007, A&A, 468, 33
- Elmegreen, B.G., Elmegreen, D.M., 2006, ApJ, 650, 644
- Erb, D.K., Steidel, C.C., Shapley, A.E., Pettini, M., Reddy, N.A., Adelberger, K.L., 2006, ApJ, 647, 128
- Genzel, R., Tacconi, L. J., Eisenhauer, F., et al., 2008, ApJ, 687, 59
- Gialalisco, M., Ferguson, H. C., Koekemoer, A. M., et al., 2004, ApJ, 600, L93
- Immeli, A., Samland, M., Gerhard, O., Westera, P., 2004, A&A, 413, 547
- Kroupa, P., 2001, MNRAS, 322, 231
- Masjedi, M., Hogg, D.W., Blanton, M.R., 2008, ApJ, 679, 260
- McCracken, H.J., Capak, P., Salvato, M., et al., 2009, ApJ, submitted
- Noeske, K.G., Weiner, B. J., Faber, S. M., et al., 2007, ApJ, 660, L43
- Pannella, M., Carilli, C. L., Daddi, E., et al., 2009, ApJ, 698, L116
- Renzini, A., 2006, ARA&A, 44, 141
- Salpeter, E.E., 1955, ApJ, 121, 161
- Santini, P., Fontana, A., Grazian, A., et al., 2009, A&A, in press, arXiv:0905.0683S
- Vanzella, E., Cristiani, S., Dickinson, M., et al., 2008, A&A, 478, 83
- Zoccali, M., Lecureur, A., Barbuy, B., et al., 2006, A&A, 457, L1